# Low Energy e+e- Colliders Ivan Koop, BINP, 630090 Novosibirsk, Russia

International Conference on Technology and Instrumentation in Particle Physics, TIPP 2021

May 24-29, 2021, online format, Triumf, Canada

### Content

First generation of e-e- and e+e- colliders

Beam-beam effects and ideas on how to suppress them

Two ring approach, multibunch operation mode

Flat versus round beam optics

Crab-Waist concept and its implementation in few new designs

Prospects and Conclusion

### First generation e+e- colliders

Colliders era begins in 60-th with ADA (Frascati, Italy), VEP-1 (BINP, Novosibirsk, Russia) and Princeton-Stanford CBX (Stanford, USA). With small delay these first colliders were followed with VEPP-2 at Novosibirsk, ACO at Orsay, France, and **ADONE** at Frascati, Italy.

The luminosity of first colliders did not exceed few units of 10<sup>28</sup> cm<sup>-2</sup>s<sup>-1</sup>. This was mainly due to very high value of the vertical beta function  $\beta_v$  at IP and very low collision frequency.

The next generation of colliders pursued the idea of compressing the magnitude of the vertical beta function at IP to few centimeters:  $\beta_v$  was made comparable with the length of the bunch. That were VEPP-2M at BINP, SPEAR at SLAC, **DORIS** at DESY and few other colliders. This gave an increase in luminosity of about two orders of magnitude.

# AdA and VEP-1 as museum showpieces





#### Precise energy calibration using the resonant depolarization technique

The Sokolov-Ternov mechanism provides fast enough self-polarization of e+e- beams by SR. This was confirmed experimentally at VEPP-2 and ACO in late 60-th.

At low energies the Touschek polarimeter became most suitable for the control of beam polarization. At higher energies most promising is the laser light Compton back-scattering technique.

Since 70th were measured using the resonant depolarization method the masses of all quarkonium bound states up to Y-family. This technique was developed initially in BINP at VEPP-2M and VEPP-4 and later refined and futher developed in other labs.

At VEPP-2M in 1987 it was done an experiment on comparision of anomalous magnetic moments of electrons and positrons at relativistic energies.

One of the most remarkable achievement was also an extremely precise mass determination of Z-peak at LEP in CERN. Koop, e+e- colliders 5

## Beam-beam effects and ideas on how to suppress them

Neglecting the hour glass effect and assuming equal number of particles N and of the transverse beam sizes one can write the luminosity formula as:

$$L = \frac{N^2 f}{4\pi\sigma_x \sigma_y}$$

This can be rewritten via the space charge beam-beam parameter:

$$\xi_{y} = \frac{r_{e}N\beta_{y}}{2\pi\sigma_{y}(\sigma_{x} + \sigma_{y})} \longrightarrow \qquad L = \begin{cases} \frac{\gamma N\xi_{y}f}{2r_{e}\beta_{y}} & \text{(flat beams)} \\ \frac{\gamma N\xi_{y}f}{r_{e}\beta_{y}} & \text{(round beams)} \end{cases}$$

Round symmetry of the shape of colliding beams gives much larger profit in luminosity than just factor 2 due to increase of the attainable beam-beam parameter: about  $\xi_{\nu} = 0.13$  for round beams instead of  $\xi_v = 0.05$  for flat beams.

This fact was in the basis for our decision to built the unique collider VEPP-2000 with round beams at BINP. In comparison with VEPP-2M we get more than a factor of 10 for the luminosity. 6

## VEPP-2000 e+e- collider with 13Tesla solenoids for FF

Design parameters @ 1 GeV		Achieved
Circumference	24.388 m	
Beam energy	150 ÷ 1000 MeV	160-1005
N of bunches	1×1	
N of particles	1×10 <sup>11</sup>	0.9×10 <sup>11</sup>
Betatron tunes	4.14 / 2.14	
Beta*	8.5 cm	
BB parameter	0.1	
Luminosity	$1 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$	0.5×10 <sup>32</sup>



K-500

Storage Ring

Bldg.13



• 13 T solenoids for FF

Linac



Bldg.1R

Operating with IC#VEPP-5 since 2016

## Round beams concept

Axial symmetry of the beam-beam kick + X-Y transport matrix symmetry from IP



The resonance chart

becomes less dense;

Higher beam-beam limits!

#### Requirements to the optics:

- Head on collision
- Equal β-functions at IP:
- Equal transverse emittances:
- Equal fractional parts of tunes:





## VEPP-2000 luminosity vs beam energy dependence



# Double ring colliders: first attemps

At DESY in 70-th one of the first double ring machine was built – DORIS. H. Nesemann, et al: Particle Accelerator Conf. (1983) 1998.

In this machine beams were brought into collision with vertical dipoles in the IR and had a vertical crossing angle. Unfortunatelly, very strong synchro-betatron resonances severely limited the attainable beam-beam tune shifts and subsequently the luminosity. After these dramatic studies DORIS was converted to operation in a single ring mode and made significant contribution to B-meson physics.

An attempt to increase the luminosity via compensation of the beam-beam space charge was done at Orsay where the four bunches collision scheme at DCI was implemented. In this machine two rings were vertically separated and e+e- bunches in each ring rotate in opposite directions relative to another ring. By vertical magnetic bends four bunches (2e+ and 2e-) are merged at the IP and the total their space charge is zero. In spite of very accurate orbit tuning severe coherent and incoherent beam-beam instabilities were observed and can't be cured. Most of the time DCI was operated with two single rings independently, doubling the luminosity. J. LeDuff, et al: XI High Energy Accelerator Conf. (1980) 566.

# Multibunch double ring colliders

Single ring colliders, such as PEP, CESR, LEP, VEPP-4, DORIS, PETRA and few others operated very well with dozens of circulating bunches but their performance was limited by low collision frequency.

Breakthrough was done by teams at SLAC , KEK and Frascati labs with B- and Phi-factories projects: PEP-II, KEKB and DAFNE.

Multibunch operation mode supplemented with the top up injection scheme resulted in a huge luminosity increase: by 2 orders of magnitude at least in comparison with previous machines!

PEP-II and KEKB with thousands of circulating bunches in each ring reached the luminosity of up to (1.2-2.1) ·10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup>.

At DAFNE operated with much lower beam energies the luminosity was obtained above 4.5  $\cdot 10^{32}$  cm<sup>-2</sup>s<sup>-1</sup>.

# Crab Waist (CW) concept

In course of SuperB proposal P. Raimondi suggested a concept of crab waist collision scheme. See P. Raimondi: 2nd SuperB Meeting, Frascati (2006); P. Raimondi, D. Shatilov, M. Zobov, in Proceedings of EPAC08, Genoa, Italy:2620-2622,2008.

This concept was successfully proved at DAFNE in special runs without the detector field. Now almost all new projects are relying on that approach, including FCC-ee at CERN and CEPC in China. In Novosibirsk we also intend to built the Tau-Charm factory and small mu-mu-tron collider with this principle in the basis.

Main idea of the CW is to install downstream and upstream from IP two special sextupoles which modify the vertical beta-function at IP in such a way, that longitudinal position of a waist is proportional to the *x*-coordinate.



Particles in one beam shall collide with other beam always at its axis. This dramatically reduces modulation of the beam-beam tune shift. That modulation is caused by crossing angle geometry.

A large intersection angle and small horizontal emittance allows us to reduce the vertical beta function value to few submillimeters!

### KEKB upgrade to SuperKEKB



From Y. Ohnishi report at 15-th KEKB review, Feb/15-17/2010

## Comparison of parameters KEKB/SuperKEKB

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
$\beta_y^*$ (mm)	10/10	5.9/5.9	0.27/0.41
ε <sub>x</sub> (nm)	18/18	18/24	3.2/2.4
σ <sub>y</sub> (μm)	1.9	0.94	0.059
ξγ	0.052	0.129/0.090	0.09/0.09
$\sigma_{z}$ (mm)	4	~ 6	6/5
I <sub>beam</sub> (A)	2.6/1.1	1.64/1.19	3.6/2.62
N <sub>bunches</sub>	5000	1584	2503
Luminosity (10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup> )	1	2.11	80

#### Luminosity expectations at SuperKEKB



#### The Novosibirsk Super Charm-Tau Factory Project

A.Bogomyagkov et al., talk given at the 2020 joint international workshop for Super-Charm Tau Facility, Pol e-1.5 GeV e-16-18 November 2020 2.5 GeV e-1.5 Gever bypass 1.5 GeV e+ e+ DR 50 m 100 m 1.5 GeV e-Novosibirsk Super Charm Tau Factory 1...3 GeV e-e+ e+ DR – positron damping ring DW - damping wiggler DW SS – Siberian Snake SS3 CV - electron-positron converter Pol e-/e- - polarized/un-polarized electron DW source SS1

C-tau parameters 2020 vs 2019

- Minimal energy increased to  $E_{beam} = 1.5 \text{ GeV}$ 
  - Relaxed lattice
  - $E_{beam} < 1.5$  GeV is possible, but not priority

• Increased, 
$$\begin{cases} \beta_y^* = 0.5 \rightarrow 1mm \\ \beta_x^* = 5 \rightarrow 10cm \end{cases}$$

- K.Oide's type of Interaction Region
- FODO  $90^{\circ}$  cells in the arcs
  - weaker sextupoles
  - more sextupoles

E(MeV)	1500	2000	3000
Π <b>(m)</b>		622.712	
<i>F<sub>RF</sub></i> (MHz)		350	
q		727	
$2\theta$ (mrad)		60	
$\varepsilon_{\gamma}/\varepsilon_{\chi}$ (%)		0.5	
$\hat{\beta_{x}^{*}}(mm)$		100	
$\beta_y^*$ (mm)		1	
α		$2.5  imes 10^{3}$	
I(A)	2	2	2
$N_{e/bunch} \times 10^{-10}$	8	6	10
N <sub>b</sub>	323	431	259
$U_0$ (keV)	17	53	270
<i>V<sub>RF</sub></i> ( <b>k</b> V)	1200	1200	2000
$\nu_s$	0.0153	0.0132	0.0139
δ <sub>RF</sub> (%)	1.6	1.4	1.4
$\sigma_e \times 10^3$ (SR/IBS)	0.27/0.9	0.4/0.7	0.5/0.6
$\sigma_s$ (mm) (SR/IBS)	4/15	7/12.6	10/11
$\varepsilon_{\chi}(nm)$ (SR/IBS)	3/22	6/12.8	12/13.7
$L_{HG} \times 10^{-35} (cm^{-2}s^{-1})$	0.4	0.5	1
$\xi_{x}$	0.005	0.005	0.007
ξ	0.08	0.072	0.09
$ au_{\mathrm{Touschek}}$ (s)	4200	2000	2600
$ au_L$ (s) Koop, e+e- colliders	2800	3200	1 <sup>1</sup> 731

#### C-tau: Lattice and layout



## C-tau: Machine-detector interface



## C-tau: Longitudinal Polarization vs e-beam energy

An equilibrium beam polarization strongly depends on energy and of a beam lifetime (top up injection regim is assumed).



A.V. Bogomyagkov, V.P. Druzhinin, E.B. Levichev, A.I. Milstein, S.V. Sinyatkin, <u>https://arxiv.org/abs/1708.05819</u>

- Dimuonium, bimuonium or true muonium is a lepton atom ( $\mu^+\mu^-$ ).
- From 6 leptonic atoms (e<sup>+</sup>e<sup>-</sup>), (μ<sup>+</sup>e<sup>-</sup>), (μ<sup>+</sup>μ<sup>-</sup>), (τ<sup>+</sup>e<sup>-</sup>), (τ<sup>+</sup>μ<sup>-</sup>), (τ<sup>+</sup>τ<sup>-</sup>) only two (e<sup>+</sup>e<sup>-</sup>), (μ<sup>+</sup>e<sup>-</sup>) were observed.
- Dimuonium is pure QED system (no strong interaction, calculable).
- Very compact (large  $m_{\mu}$ ), more sensitive to new physics than other exotic atoms.

V.N.Baier and V.S.Synakh, Bimuonium production in electron-positron collisions, SOVIET PHYSICS JETP, **14**, № 5, 1962, pp.1122-1125

#### Properties of the bound state, probability of observation

S.J. Brodsky and R.F. Lebed. Production of the Smallest QED Atom: True Muonium ( $\mu^+\mu^-$ ). Phys. Rev. Lett., 102:213401, 2009

Very large crossing angle in order to eliminate background

H. Lamm and R.F. Lebed, True Muonium ( $\mu^+\mu^-$ ) on the Light Front, arXiv 1311.3245v3, 12 Nov 2014

#### Spectrum

H. Lamm, True muonium: the atom that has it all, arXiv 1509.09306v1, 30 Sep 2016 *Novel properties* 



#### mu-mu-tron: e+e- large crossing angle collider project at BINP

A.V. Bogomyagkov, V.P. Druzhinin, E.B. Levichev, A.I. Milstein, S.V. Sinyatkin, https://arxiv.org/abs/1708.05819



#### Mu-mu-tron optics – implementation of Crab-Waist concept

		-
Beam energy	408 MeV	
Circumference	23 m	
Momentum compaction	6.4×10 <sup>-2</sup>	m), ß, (m)
Bunch intensity	3.5×10 <sup>10</sup> / 73 mA	β. (i
Horizontal emittance	26 nm 90 nm (IBS)	
Energy spread	4×10 <sup>-4</sup> 8.4×10 <sup>-4</sup> (IBS)	
β <sub>x</sub> / β <sub>y</sub>	200 mm / 2 mm	
Luminosity	4×10 <sup>30</sup> cm <sup>-2</sup> s <sup>-1</sup> , Nb=1 8×10 <sup>31</sup> cm <sup>-2</sup> s <sup>-1</sup> , Nb=20	



#### Prospects and Conclusion

- FCC-ee at CERN and CEPC in China with beam energies up to 2 x 180 GeV, both having 100 km circumference, are expecting to be the next discovery machines at and beyond the Higgs boson threshold.
- SuperKEKB team consider future upgrade with longitudinally polarirized electrons. That will significantly widen the collider's capability to examine the electroweak sector.
- Tau-Charm factories in Novosibirsk and Hefei will perform experiments in very rich energy range with beam energies up to 2 x 3 GeV. The longitudinal polarization of the electron beam shall provide complementary possibilities to study CP-violation.
- Crab-Waist approach became the key technology in reaching the highest luminosity of future e+e- colliders.
- New ideas and diagnostic tools will help futher increase the collider's luminosity.